Direct estimation of sea state impacts on radar altimeter sea level measurements

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Received 1 July 2002; accepted 9 September 2002; published 17 December 2002.

[1] A new sea state bias modeling approach is presented that makes use of altimeter-derived marine geoid estimates. This method contrasts with previous models that require differencing between repeat altimeter passes for SSB isolation, along with complex bivariate inversion, to derive a relation between wind speed, wave height and SSB. Here one directly bin-averages sea height residuals over the wind and wave correlatives. Comparison with the most current nonparametric repeat-pass model shows close agreement and provides a first validation of this simpler and more direct technique. Success is attributed mainly to extensive space and time averaging. Ease in implementation and benefits in working with absolute levels provide much appeal. Further advantages and potential limitations, centered on the need to effectively randomize large sea level anomaly components to expose the bias, are also discussed. *INDEX TERMS:* 1640 Global Change: Remote sensing; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4504 Oceanography: Physical: Air/sea interactions (0312); 6959 Radio Science: Radio oceanography; 4215 Oceanography: General: Climate and interannual variability (3309). **Citation:** Vandemark, D., N. Tran, B. D. Beckley, B. Chapron, and P. Gaspar, Direct estimation of sea state impacts on radar altimeter sea level measurements, *Geophys. Res. Lett.*, *29*(24), 2148, doi:10.1029/2002GL015776, 2002.

1. Introduction

[2] The SSB in a satellite altimeter's range measurement results in a sea level estimate that falls below the true mean. Modeled SSB correction uncertainty is thought to be 1.5–2 cm on average and can exceed 5 cm in high seas [*Chelton et al.*, 2001].

[3] A location's sea surface height (*SSH*) measurement, uncorrected for SSB, contains the geoid signal (h_g), the ocean dynamic topography (η), the SSB, and other measurement and correction factors (w):

$$SSH = h_g + \eta + SSB + w. \tag{1}$$

SSB modeling normally begins by eliminating the dominant marine geoid signal from equation (1) by differencing precise repeat measurements either along collinear tracks [*Chelton*, 1994] or at orbit crossover points [*Gaspar et al.*, 1994]. Repeating altimeter measurements typically occur within 3–17 days, thus longer-term variance in the large η term is also removed. Using the two additional radar altimeter products, radar cross section-derived wind speed (U) and significant wave height (SWH), SSB estimation relates time-dependent range differences to corresponding wave height and wind speed differences.

[4] While relatively successful, the development of empirical SSB models based on repeat-pass differences presents several limitations [*Gaspar et al.*, 2002]. Key among these is the need to develop a nonparametric model function to resolve nonlinearities obscurred within standard regression techniques operating on differenced data. In addition, residual error analysis can only be performed in the space of the differenced variables. Further, large amounts of data and complex, numerically-optimized inversions are also required to properly develop such a model.

[5] Another approach is to solve for SSB directly by imposing a constant *a priori* mean sea level at each altimeter observation location thus eliminating the geoid. While substantial errors residing within equation (1) discouraged this approach in the past, the TOPEX/Poseidon mission has now provided ten years of precise measurements along the same 254 ground tracks across the global ocean. This paper provides a preliminary demonstration of this approach using TOPEX data.

2. Methods

[6] Following equation (1), a long-term average for the sea surface at any referenced location k on an altimeter's ground track can be written as:

$$MSS_k = \left(h_g + \langle\eta\rangle + \langle SSB - SSB_{\mathrm{m}}\rangle + \langle w\rangle\right)_k \tag{2}$$

where $\langle\rangle$ denotes the expectation computed over a given time period. SSB_m are the model-derived sea state range corrections employed in this surface determination, and w comprises all other error components (e.g. in sensor range corrections, interpolation errors, orbit, tides, atmospheric terms, etc...) built into the mean sea surface MSS_k estimate. Equation (2) assumes independence between source terms.

[7] An individual height residual, $\Delta h_k = SSH_k - MSS_k$, used in SSB estimation is thus:

$$\Delta h_k = (SSB + (\eta - \langle\eta\rangle) - \epsilon_{SSB} + (w - \langle w \rangle))_k \tag{3}$$

where $\epsilon_{SSB} = \langle SSB - SSB_m \rangle$ at any k defines the time-independent SSB modeling error within MSS_k. Note that the many realizations forming every MSS_k and ϵ_{SSB} differ from the arbitrary sample denoted in equation (3). Next, let dynamic sea level variability $(\eta - \langle\eta\rangle)$ be joined with $(w - \langle w \rangle)$ to form a noise term ϵ. By design, the geoid term cancels out to give:

$$\Delta h_k = (SSB + \epsilon_{SSB} + \epsilon)_k \tag{4}$$

Error terms on the right side of the equation depend upon the quality of the estimates used to build MSS_k including, to some extent, the accuracy of the SSB model(s) used.

[8] An empirical bivariate SSB model is readily built by defining MSS_k globally and then computing the mean height bias at discrete bins across the (U, SWH) domain. Each bin holds the average over height residuals for all locations (k, ij), meeting the condition that altimeter-derived wind and wave height estimates fall within a (U_i, SWH_j) bin having width (ΔU, ΔSWH), given as:

$$SSB(U_i, SWH_j) = \langle (SSH_{ij} - MSS)_k \rangle \tag{5}$$

The ϵ terms are dropped in equation (5) under a tentative assumption of weak dependency on sea state effects and assumed convergence of η and w terms towards zero mean values under long-term global averaging.

[9] Implementing this formula using TOPEX NASA altimeter (TOPEX hereafter) data is straightforward. The sea surface height residuals used are interpolated, georeferenced values computed along the TOPEX track using an established mean sea surface [*Wang*, 2001]. This surface merges multiple years and several satellite mission data sets (TOPEX, ERS, and Geosat) along the mean tracks of TOPEX [*Koblinsky et al.*, 1998], spanning a time period from 1986 to 1999. The large time period and number of repeat measurements lead to precise geoid determinations along the TOPEX track. This provides not only a reference mean sea level for oceanic studies, but also a low noise MSS along the altimeter's ground track that was not available in past SSB investigations.

[10] Prior to computing Δh_k, TOPEX measurements are corrected for all geophysical and instrumental effects and the original SSB (version 2.0 algorithm [*Gaspar et al.*, 1994]) is removed from each height estimate. These estimates are given at 1-s along-track intervals (~every 6 km) and interpolated to fixed georeferenced track locations. All Poseidon-1 altimeter and any erroneous (using conventional data quality flagging) TOPEX estimates are eliminated. Pairing of the NASA/GSFC Altimeter Pathfinder dataset with both TOPEX radar cross section σ_0 and SWH data is accomplished using the same georeferencing interpolation. The 10-m wind speed is calculated from σ_0 using the modified Chelton and Wentz algorithm [*Witter and Chelton*, 1991]. One 10-day TOPEX cycle of pathfinder data prepared in this manner provides 350,000–400,000 samples. For direct comparison to the most current SSB model [*Gaspar et al.*, 2002] (NP02 hereafter), cycles 21–131, April 1993–April 1996, are examined. The number of samples used in this 3-year average exceeds forty million. For demonstrations here, data are not spatially subsampled to insure independence. Data set size would contract by a factor of 7–10 with such sampling. By comparison, the NP02 crossover set contains 633,000 points for the same period.

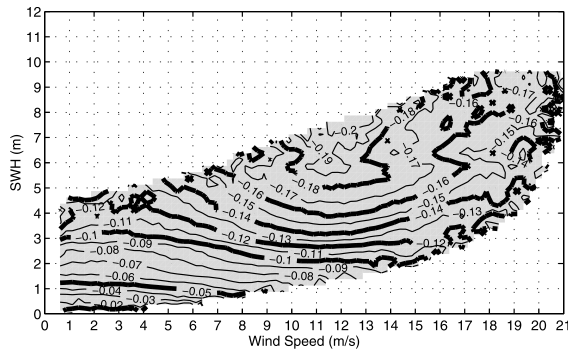

Figure 1. Isolines for the global TOPEX SSB estimate (in meters) obtained from bin-averaging into boxes of width (0.25 m/s, 0.25 m) over the (U, SWH) domain.

4. Conclusion

[18] This is the first reported direct (non-differenced) realization of on-orbit altimeter SSB impacts. The technique relies upon averaging over a numerous realizations to isolate the small SSB signature. Results from a 3-year global average mirror that obtained using satellite crossover differences and subsequent nonparametric model inversion. It is also shown that an accurate SSB estimate can be obtained over most of the altimeter-derived (U, SWH) domain with as little as 100 days of data, a substantial improvement. Direct intercomparison corroborates two separate empirical TOPEX SSB derivations, but observed mm-level offsets and estimate differences for infrequently observed locations in the (U, SWH) domain highlight the need for future refinement.

[19] There is no question that this direct method is simpler to implement from numerous perspectives, foremost the avoidance of complex and numerically-intensive non-parametric inversion. Moreover, one is now working directly with the height residual and its correlatives, rather than time-dependent differences in all terms. These points, among others, suggest the benefit that direct assessment may have in speeding studies to evaluate the relative importance of additional characteristics of sea state beyond altimeter-derived (U, SWH). For instance, direct regression of TOPEX height residuals against global model-derived long wave products, unobtainable using the altimeter, are in progress and may identify remaining SSH variance. Further, the sparse time-sampling approach of Figure 2a can also be applied spatially, where basin-scale evaluation of the sea state impacts now becomes more tractable. It is also likely that this SSB methodology is applicable to altimeters aboard ERS, Envisat, or Geosat Follow-On platforms with use of an appropriate mean surface reference.